# A High Specific Output Gasoline Low-Temperature Combustion Engine

## – 2019 US DOE VTO AMR meeting –

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June 13, 2019

*Acknowledgment*: This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007788.



**Project ID # ace121**

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*Any proposed future work is subject to change based on funding levels*

# Overview

## Timeline

Start Date: January 2017
End Date: December 2019
Duration: 3 years

**Completion: 75%**

## Goals / Barriers

- 15 ~ 17% fuel economy over baseline
- Low temperature combustion regimes for gasoline engines
- Effective engine controls for Low Temperature Combustion
- Emissions control challenges for advanced engine concepts

## Budget

Total funding for 3 years
$ 1.90 M DOE Share
$ 2.04 M GM Share
$ 3.94 M Total

Funding received in FY18: $ 456.580
Funding for FY19: $ 529,350

## Project Partners

Key Suppliers

| | |
|---|---|
| FEV | Delphi |
| Federal Moguls | BASF |

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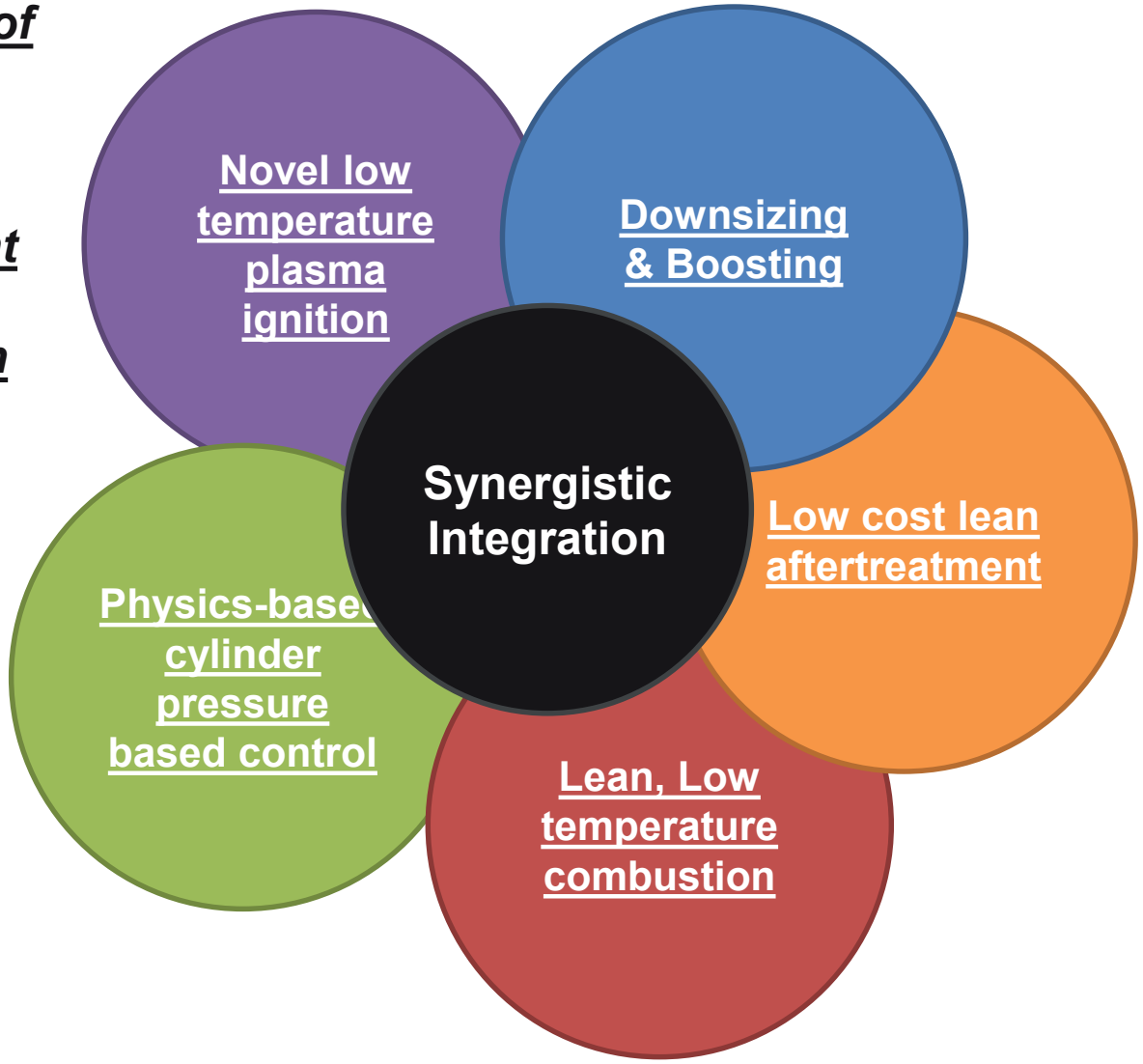
# Relevance – Objective

- The primary objective of this project is the ***development of a gasoline combustion engine system capable of demonstrating a 15-17% fuel economy improvement relative to a contemporary stoichiometric combustion engine using marketplace gasoline(RD587)***

- Be consistent with relevant emissions constraints (SULEV30)

- Advanced individual technology should be synergistically integrated to achieve this goal

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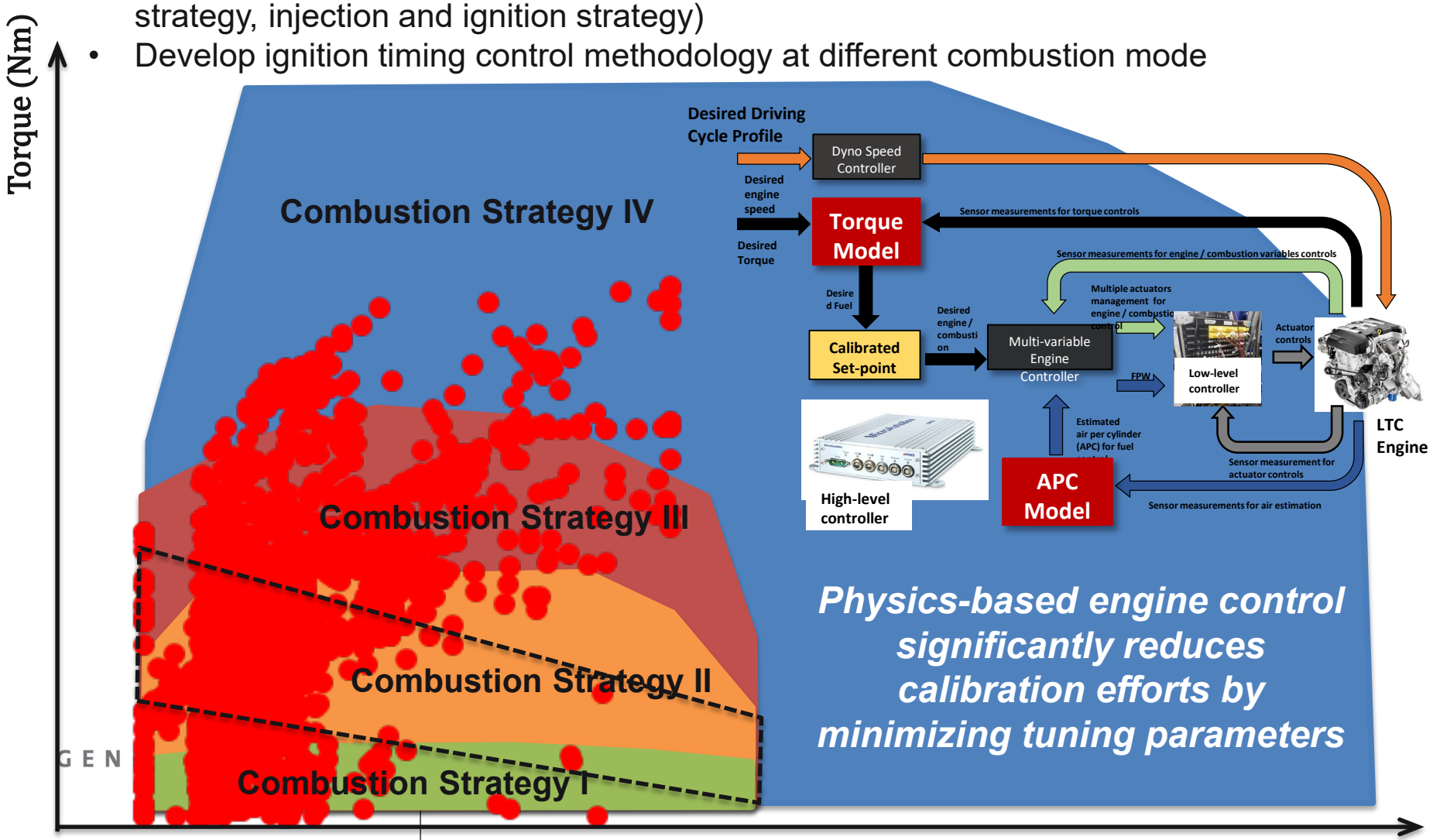
# Approach – Combustion and Control

***Development TARGET: <u>High Efficiency</u>; <u>Low NOx</u>; <u>Low Combustion Noise</u>; <u>Controllability</u>***

- Maximize LTC operation to cover the FTP cycle,
- Develop optimal LTC strategy at various operating conditions, (optimization of valving strategy, injection and ignition strategy)
- Develop ignition timing control methodology at different combustion mode

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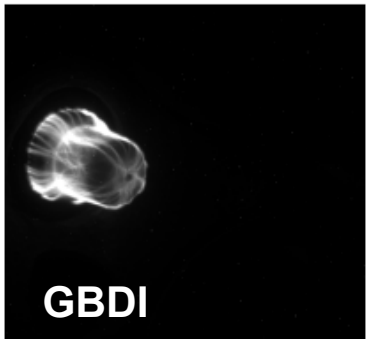
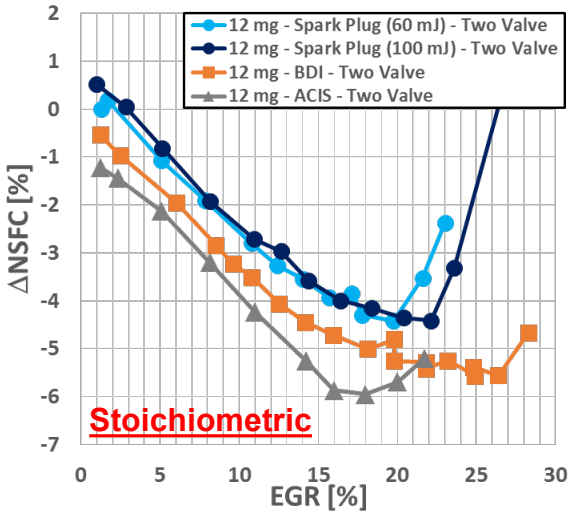
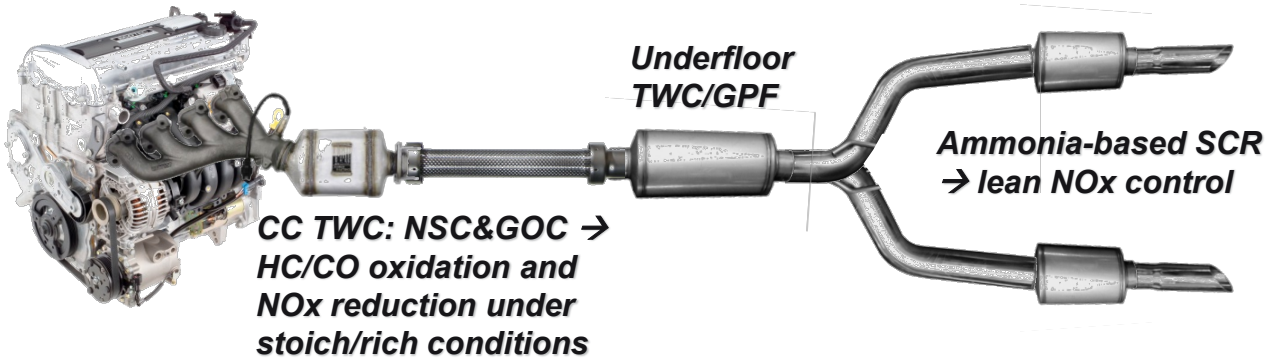
# Approach – Ignition & Aftertreatment

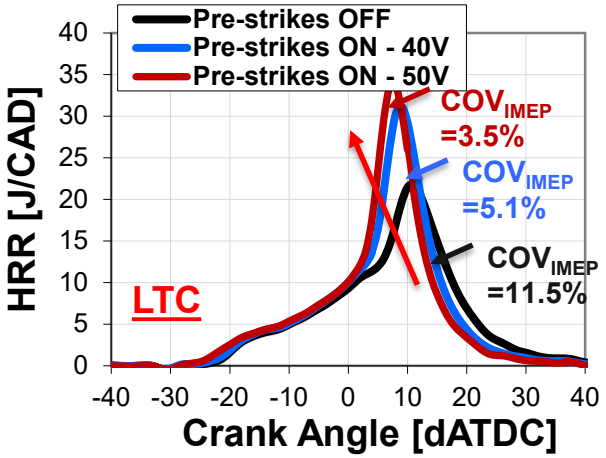



- Challenge: the higher in-cylinder pressures demands higher breakdown voltages → require smaller gap sizes → the more the stability limit is degraded.
- GM in conjunction with Federal Mogul has developed a unique GBDI (Groundless Barrier Discharge Igniter).




- The system provides superior flame-initiation under stoich conditions, as well as LTC combustion phasing control through ozone generation by simply changing the supplying voltages.




- PASS is a low cost, lean aftertreatment system that relies on the characteristics of the TWC and SCR to address stoichiometric and lean exhaust gas aftertreatment ***without the need for supplemental urea injection and/or high PGM loadings***. → Periodically operate the engine rich to generate NH3 on the TWC and store it on the SCR → Under lean conditions, use the stored NH3 on the SCR for NOx conversion.

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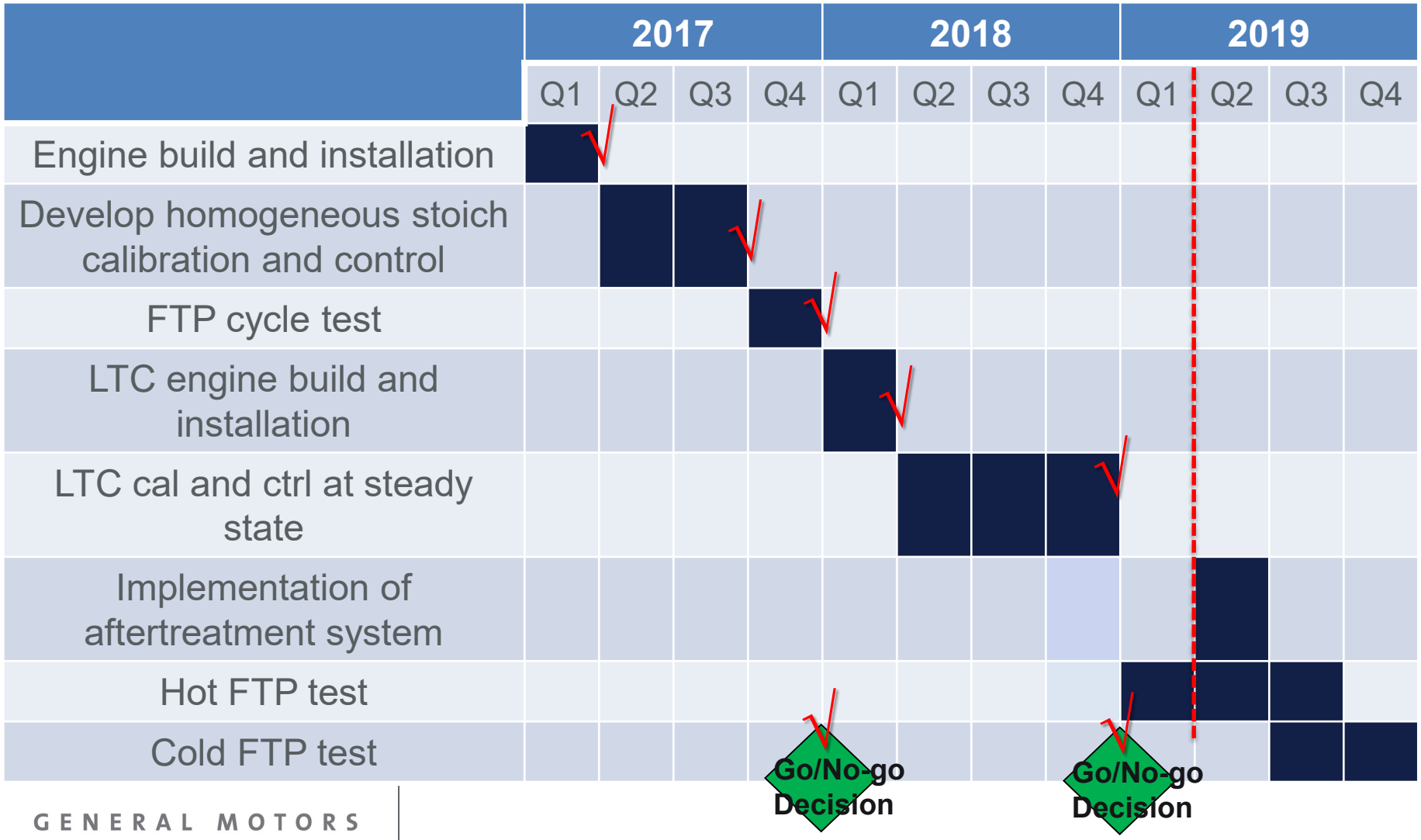
# Approach – Milestones

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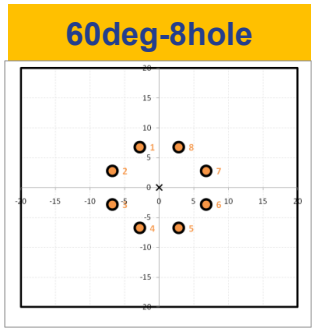
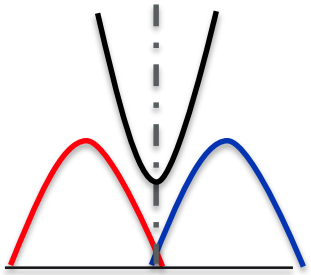
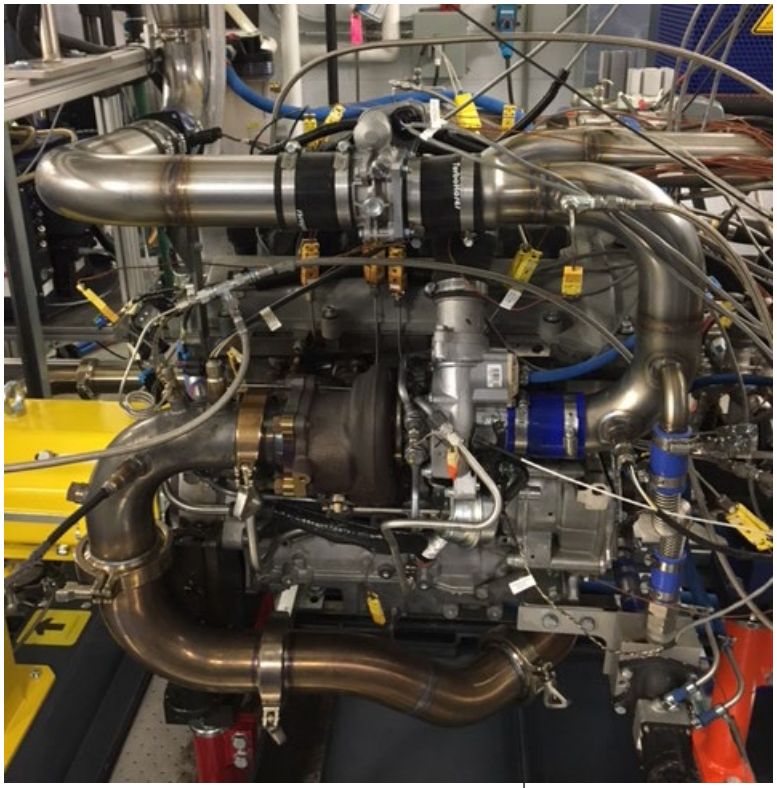
# Technical Accomplishments and Progress

## ***Baseline Engine***

- 2.2L 4-cylinder Engine
- Compression ratio = 12:1
- BOSCH 60-8 hole injector
- Conventional spark plug
- Single-step camshaft

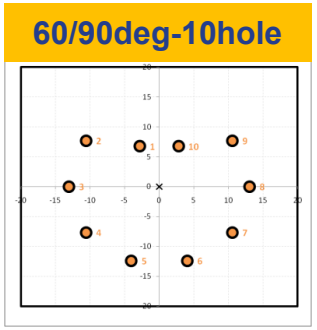


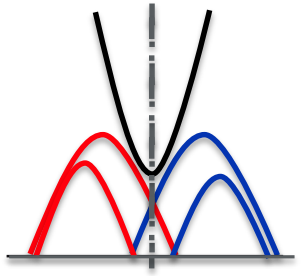





## ***LTC Engine***

- Scaled 1.4L 4-cylinder turbo-charged engine
- DELPHI 60/90-10 hole injector
- GBDI System (SPK is back-up)
- Two-step camshaft
- Turbo-charger



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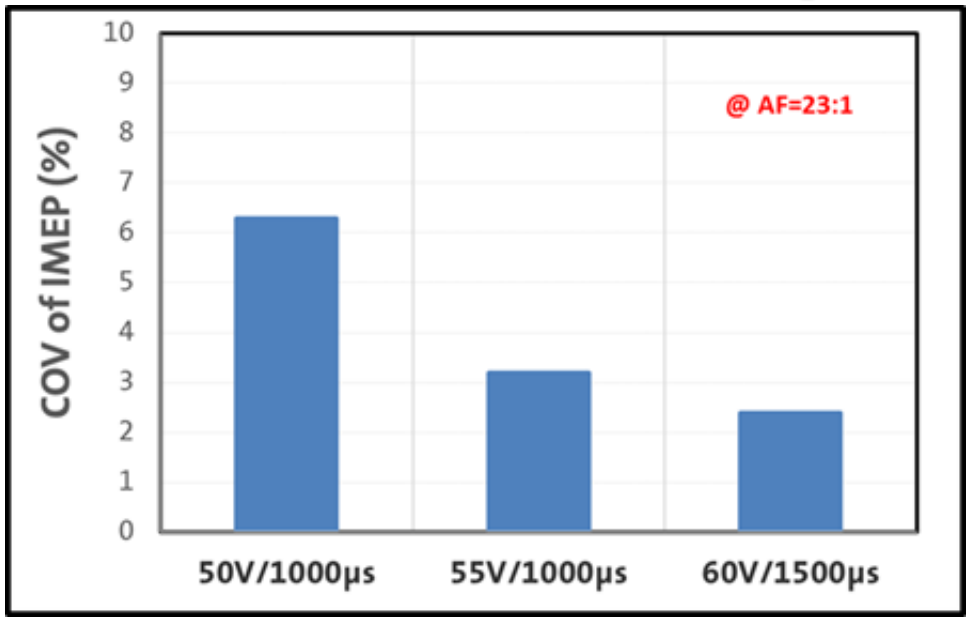
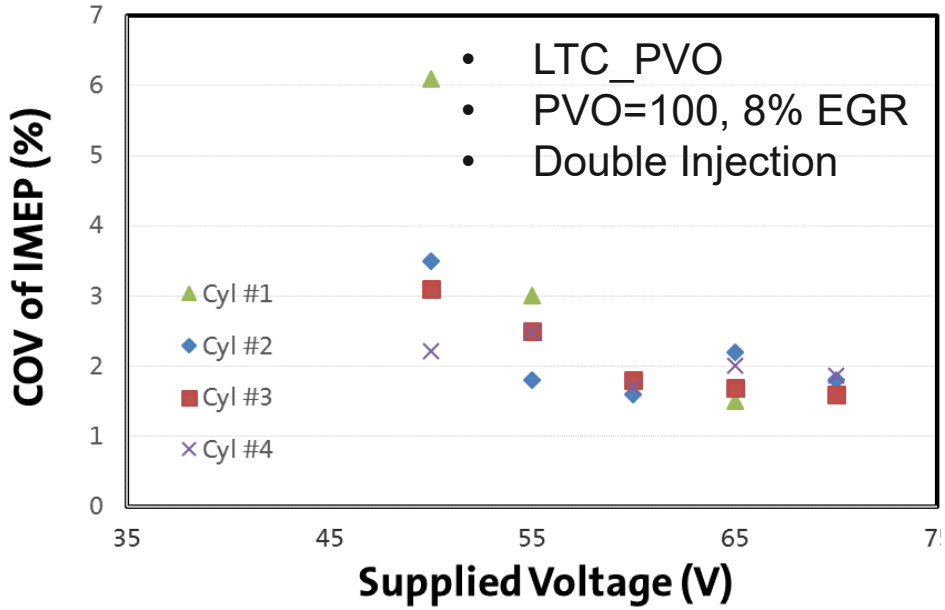
# Evaluation of GBDI System

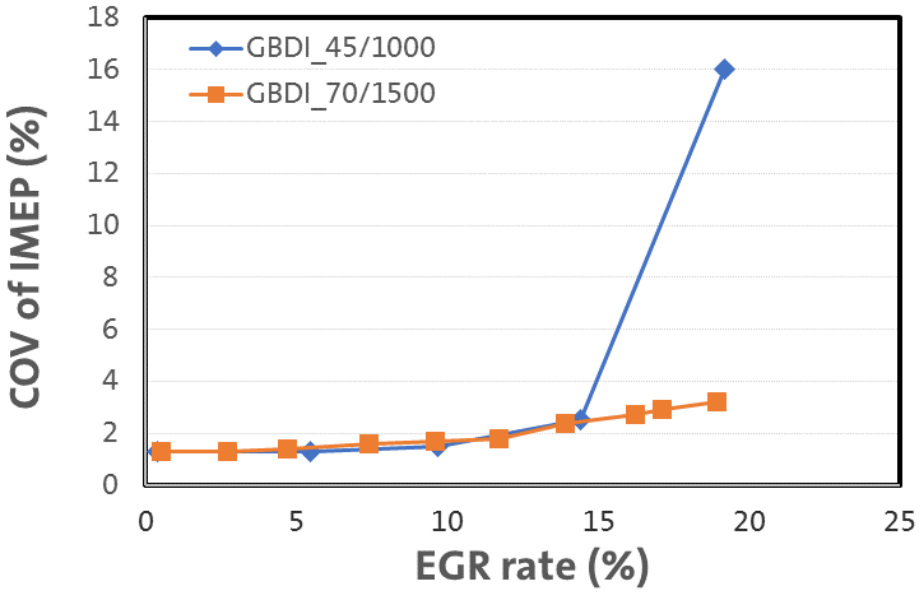
# Technical Accomplishments and Progress




- LTC_NVO Operation
- AF = 23:1
- NO EGR, single injection, single ignition

- Stoich. Operation
- EGR sweep at stoich. operation
- Single injection, Single ignition

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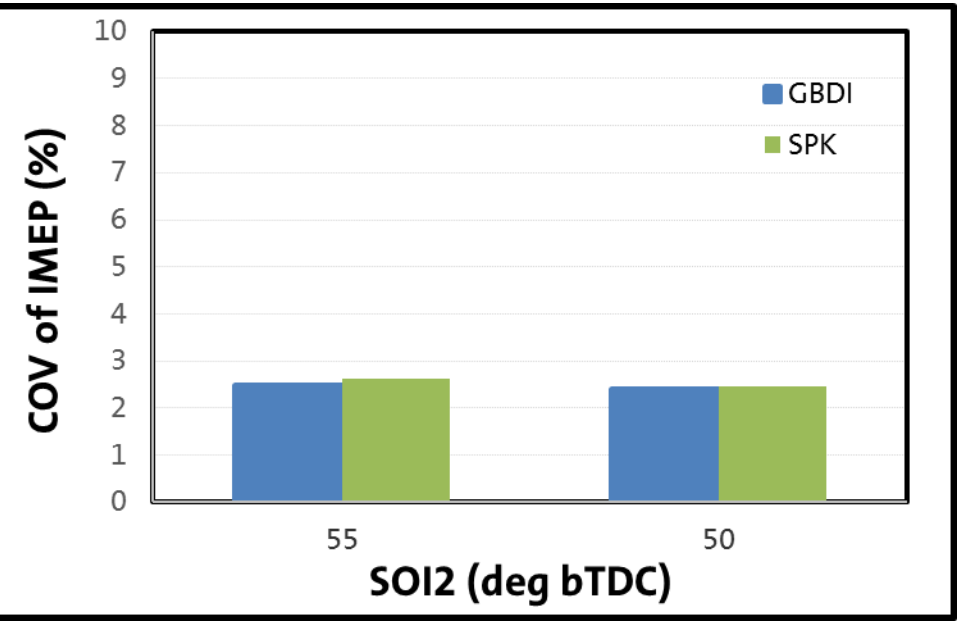
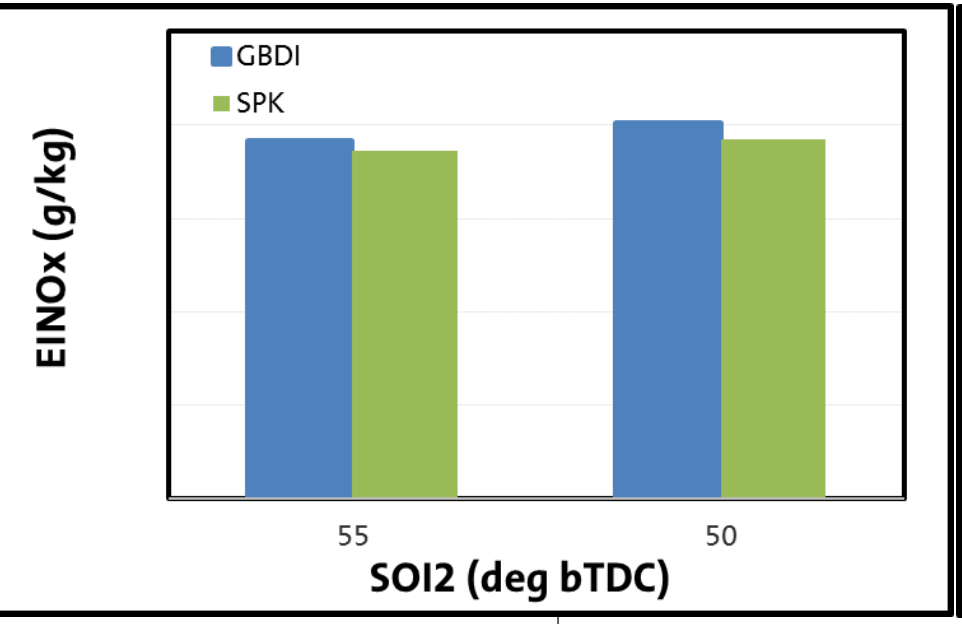
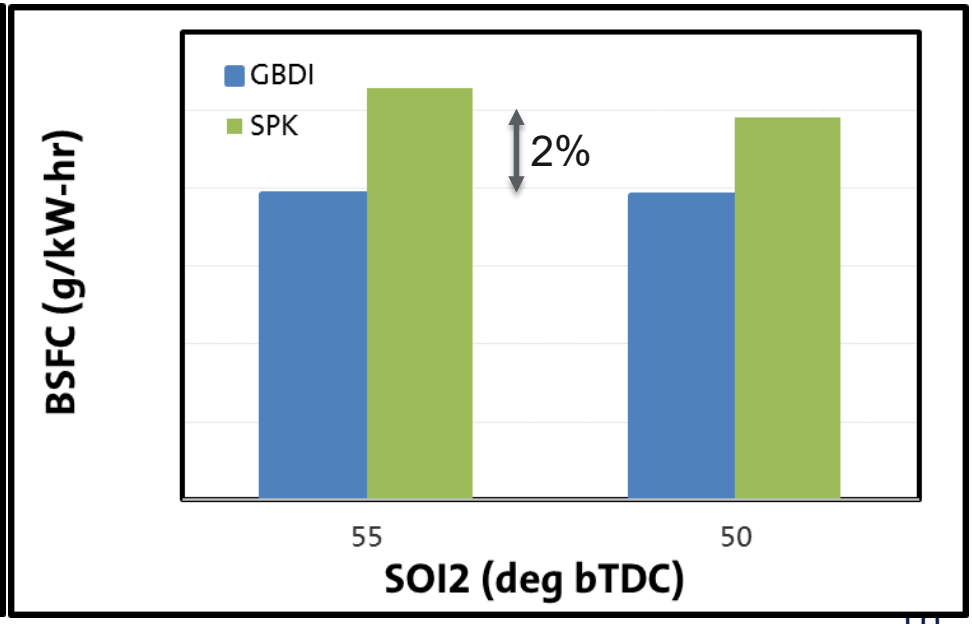
# Technical Accomplishments and Progress

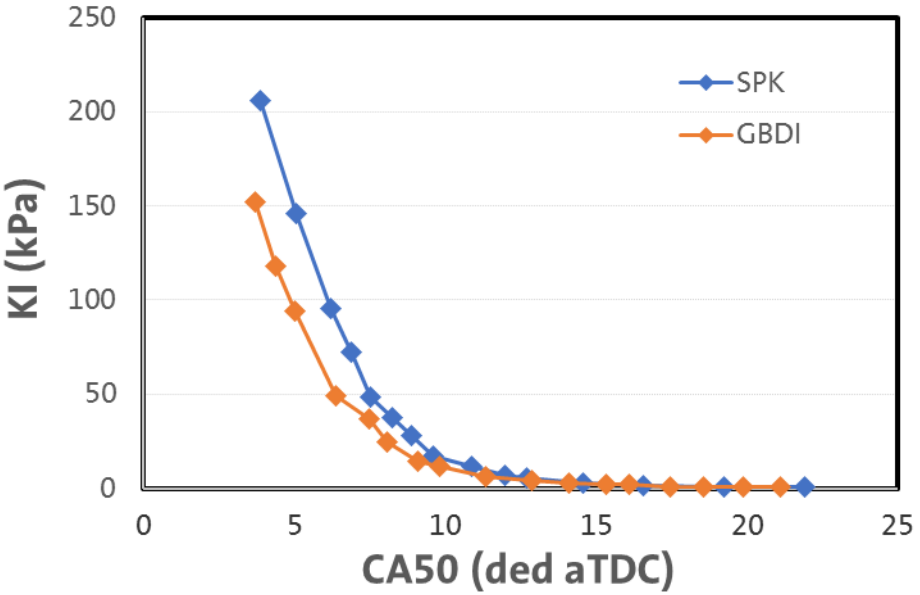



- LTC_PVO Operation
- PVO=100, 8% EGR
- Double Injection (SOI1=300 bTDC, SOI2=60 bTDC)

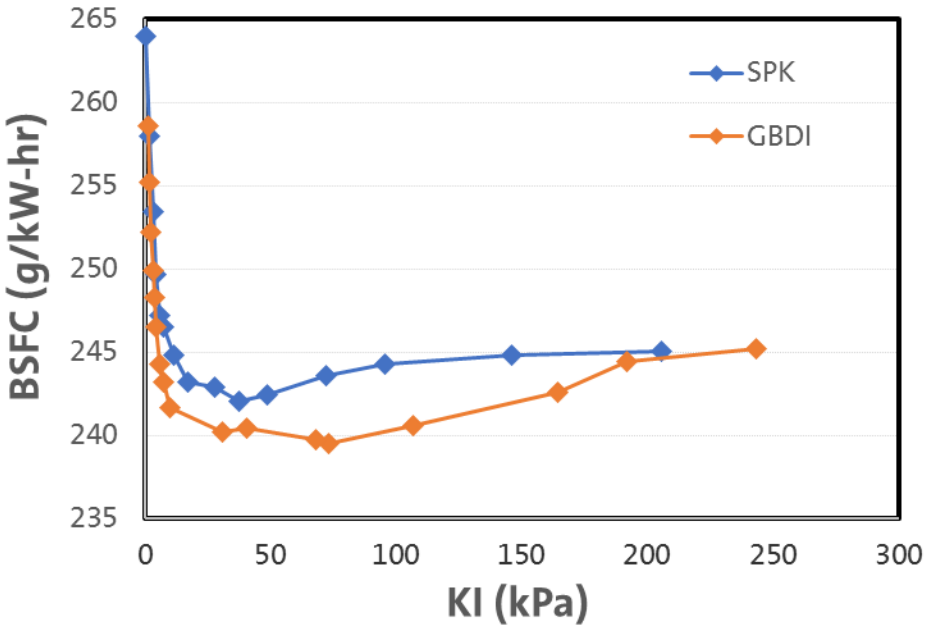


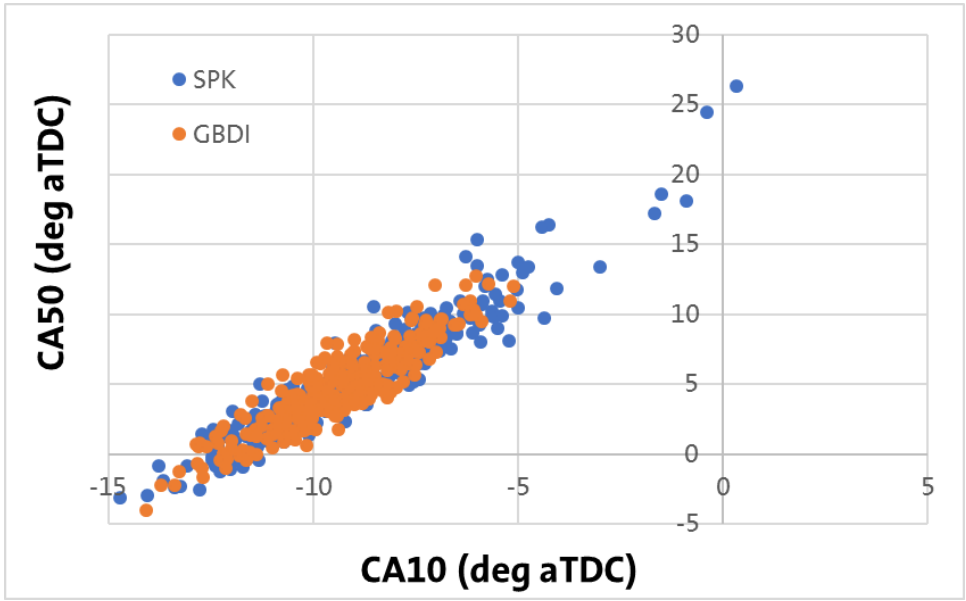



# Technical Accomplishments and Progress




- Stoich. Operation
- 2000 rpm, 26mg
- 10% EGR
- Single Injection (SOI=290 bTDC)

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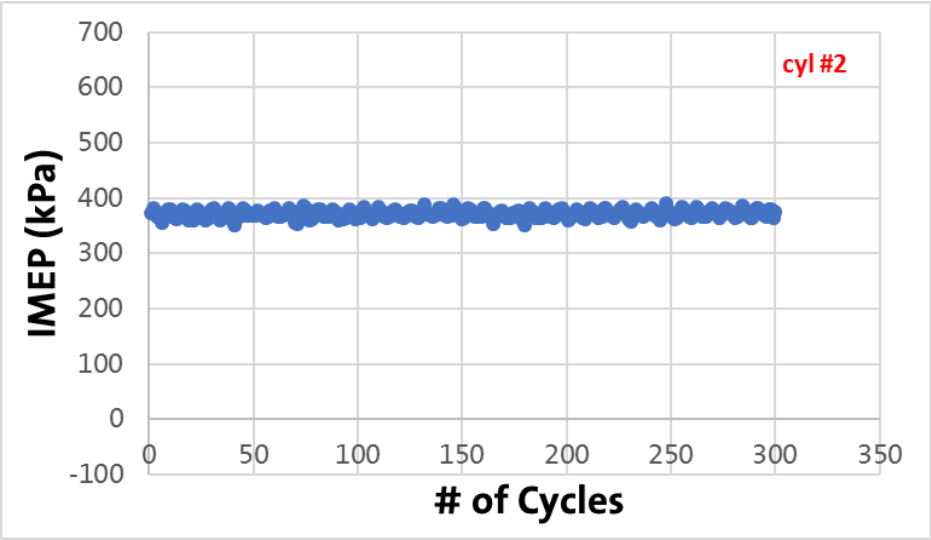
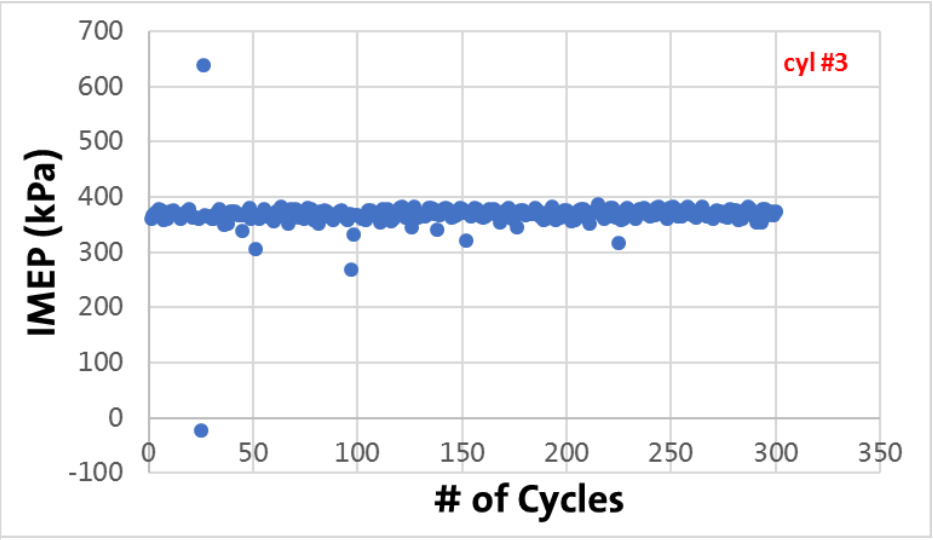
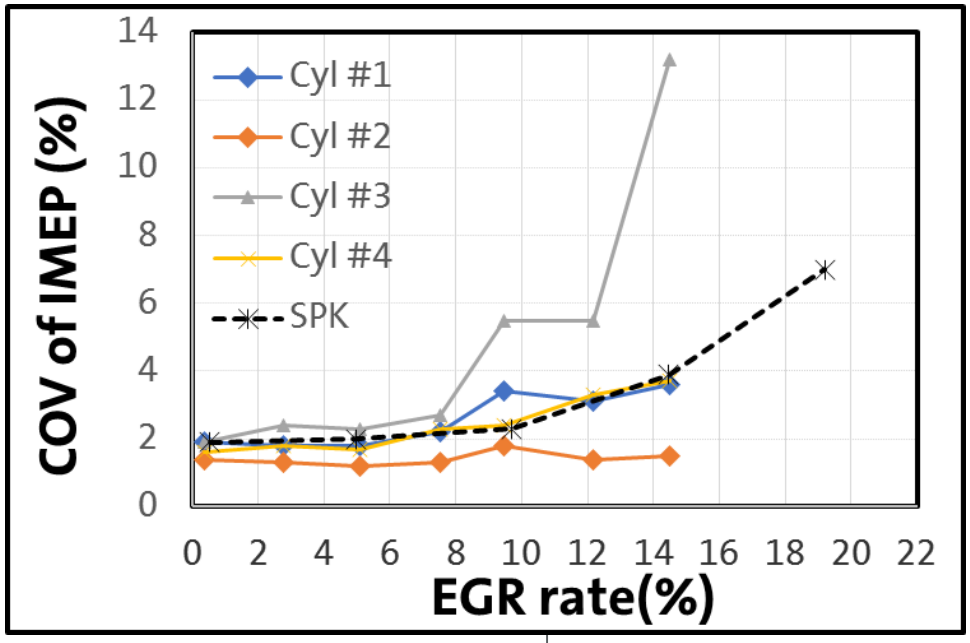
# Drawbacks of GBDI

# Technical Accomplishments and Progress




- 2000rpm, AF ratio sweep (LTC Operation)

- 1500 rpm, 11 mg (2 bar BMEP)
- EGR sweep at stoich. operation
- Single injection, Single ignition

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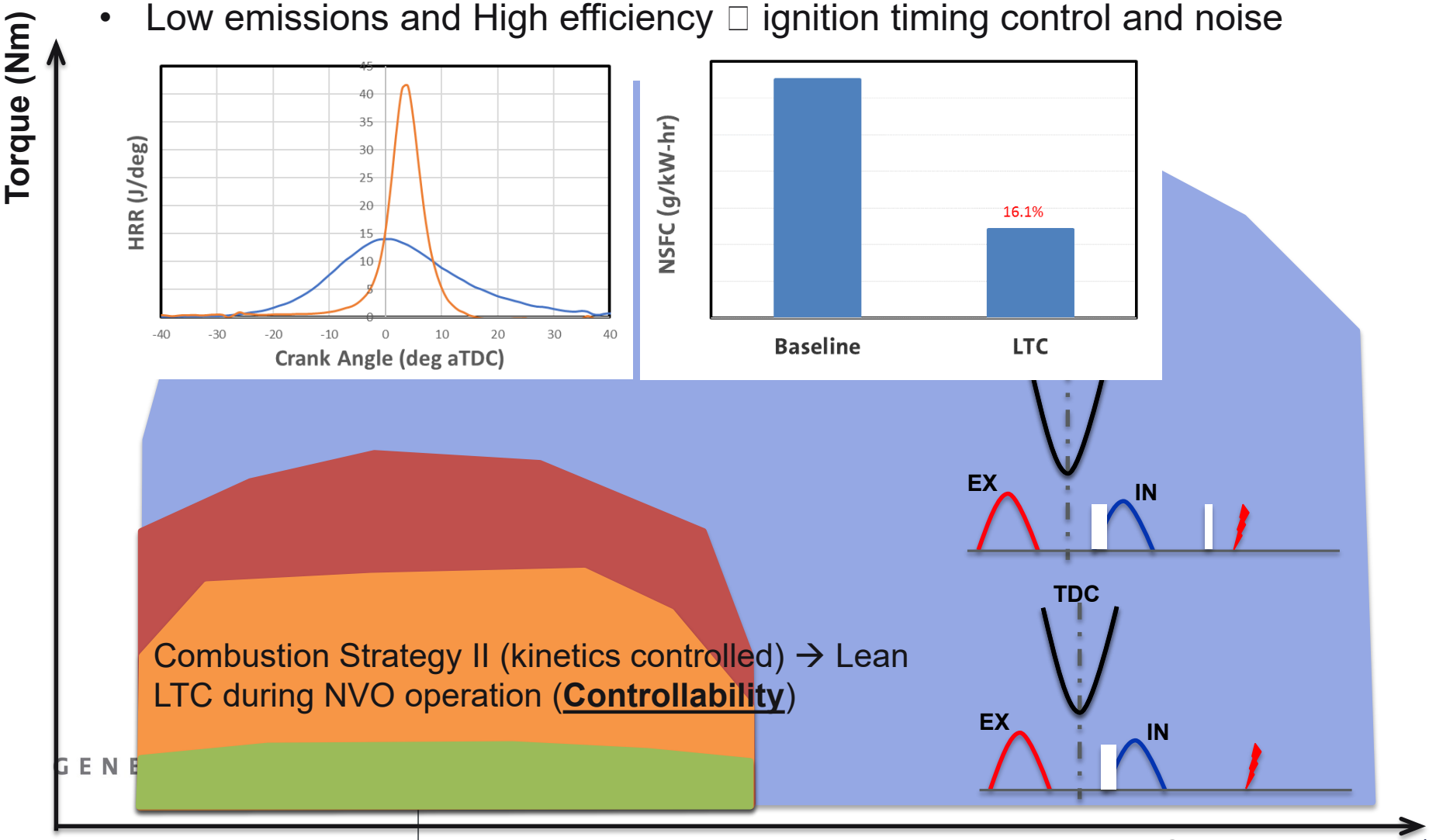
# Technical Accomplishments and Progress

- Since May 2018, 12 igniters have failed so far.

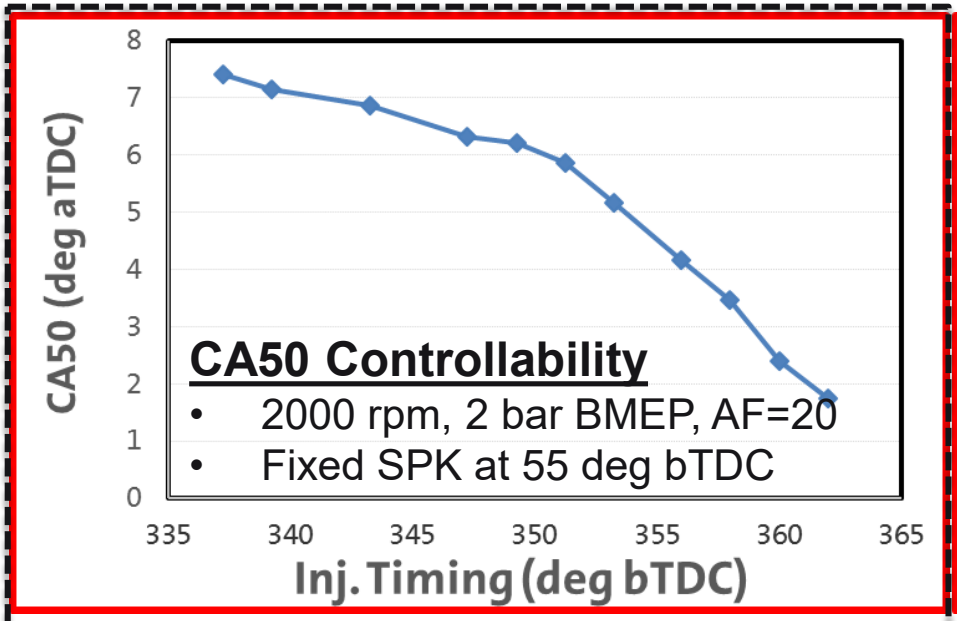
| Date | Hour | Comment |
|---|---|---|
| 5/16/2018 | 0 | Failed on start up (70V, 1.5ms); internal arcing detected on bench test. |
| 5/17/2018 | 0 | Coil Failure |
| 5/29/2018 | | Failed after battery issue; Upper swivel nut broke loose from silicone rubber |
| 6/1/2018 | | Coil Failure |
| 6/4/2018 | | Firing only on one side, significant deposit formation |
| 6/5/2018 | | Firing only on one side, no deposit formation |
| 6/7/2018 | 30 | Broke sheathing, carbon tracking |
| 6/22/2018 | 40 | Coil Failure |
| 7/26/2018 | 40 | Coil Failure |
| 8/3/2018 | **147** | Lost plasma |
| 8/9/2018 | 12 | Igniter Failure |
| 8/8/2018 | 8 | Igniter Failure |

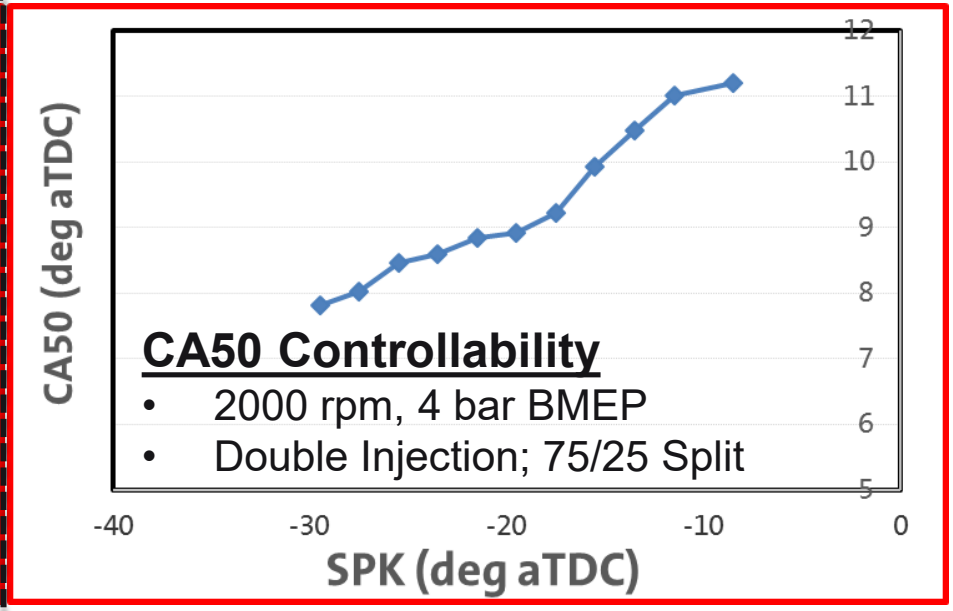
# Technical Accomplishments and Progress

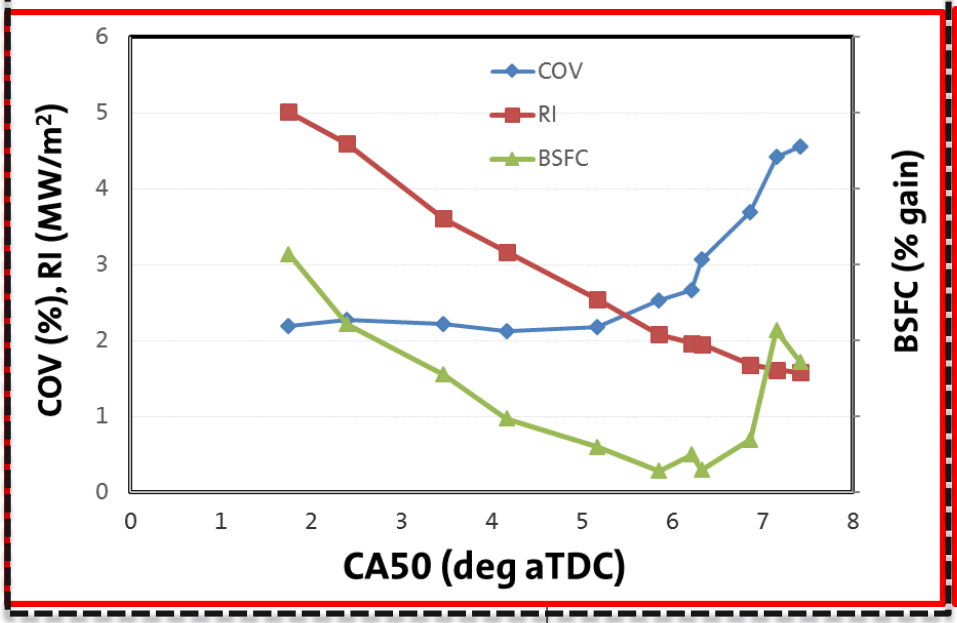
- MAP = 95 kPa (WOT); w/o or w/ EGR
- Low lift camshaft (negative valve overlap) for hot internal residuals
- Low emissions and High efficiency  ignition timing control and noise

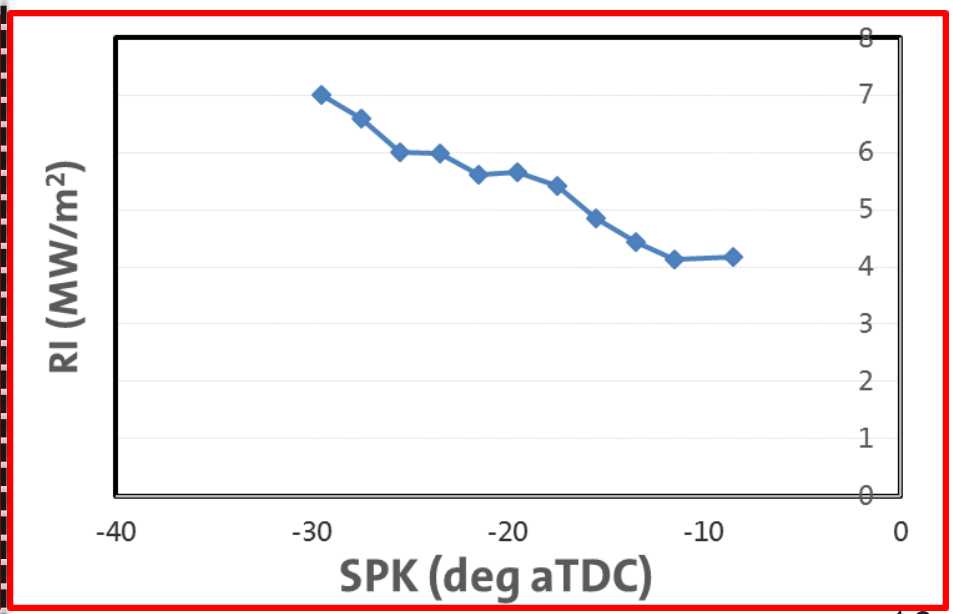


# Technical Accomplishments and Progress

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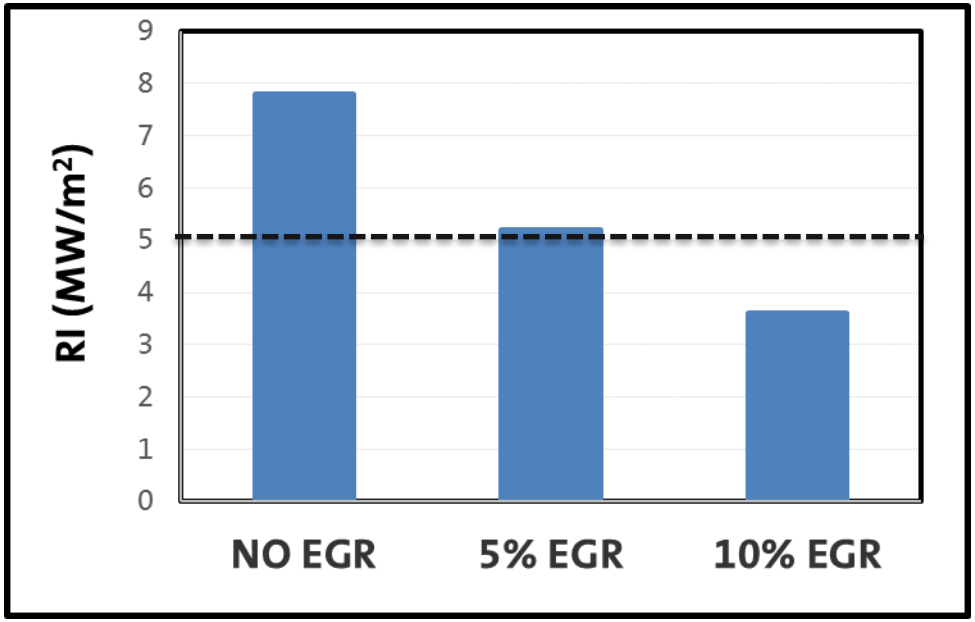
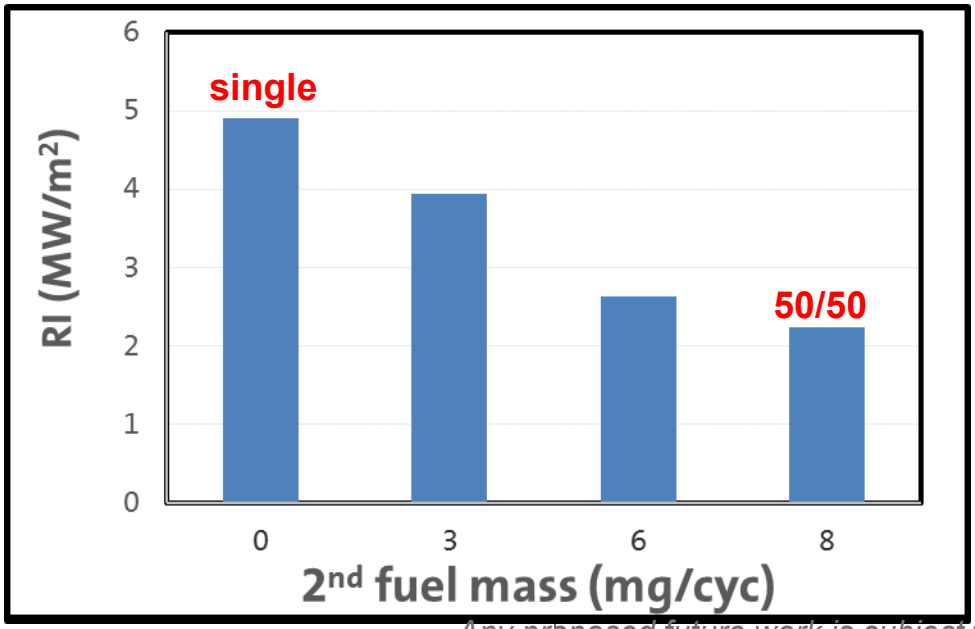
# Technical Accomplishments and Progress




## Noise Reduction

- 2000 rpm, 3.3 bar BMEP
- AF = 18
- CA50 = 7 deg aTDC
- EGR suppresses auto-ignitability of the mixture → combustion begins with flame-burn and auto-ignition takes place later in the cycle → the total burn duration is extended → ringing decreases



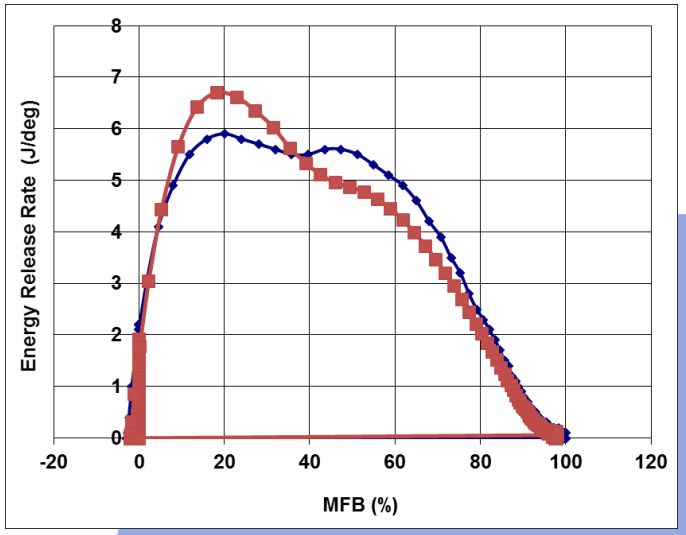

## Noise Reduction

- 2000 rpm, 4 bar BMEP
- CA50 = 9.5 aTDC
- 10% EGR

→ The more mass for 2nd injection, the lower ringing and NOx emissions due to the extended burn duration

# Technical Accomplishments and Progress

- MAP = 95 kPa (WOT); NO EGR
- Low lift camshaft (negative valve overlap) for hot internal residuals
- Combustion stability → Reforming for additional heat; flame burn for combustion robustness







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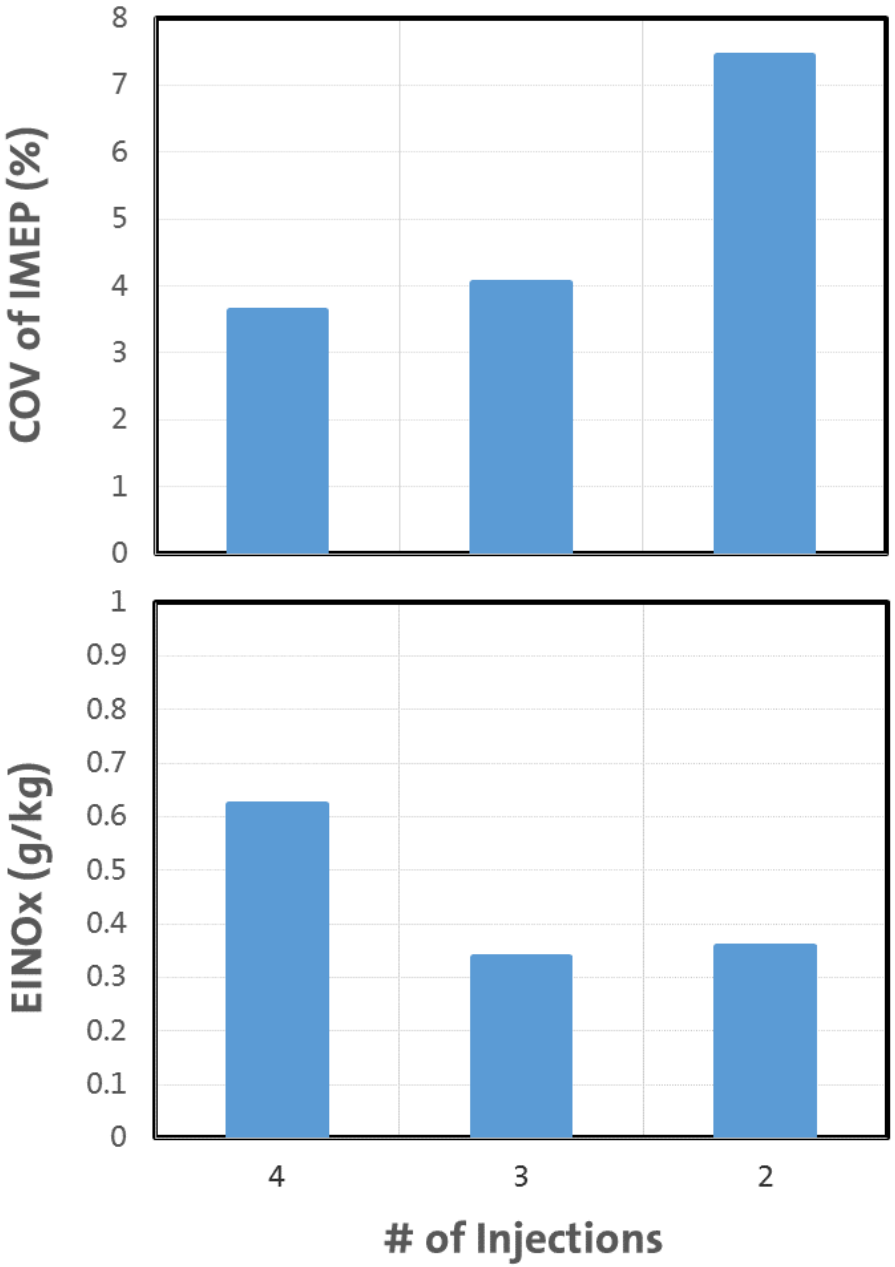
# Technical Accomplishments and Progress

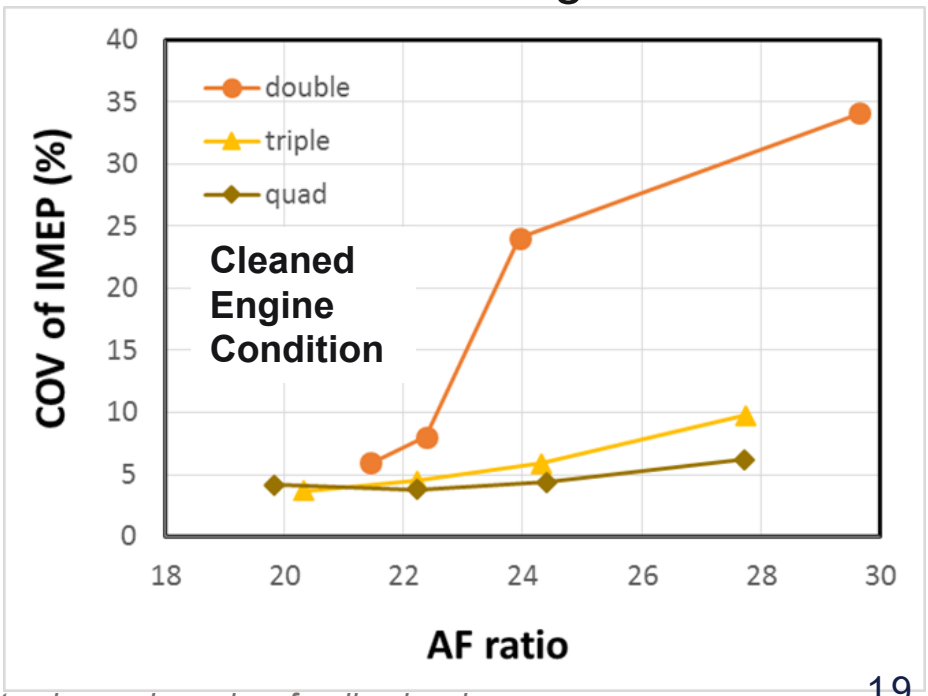



## Robustness

- 1500 rpm, 6 mg
- NO EGR

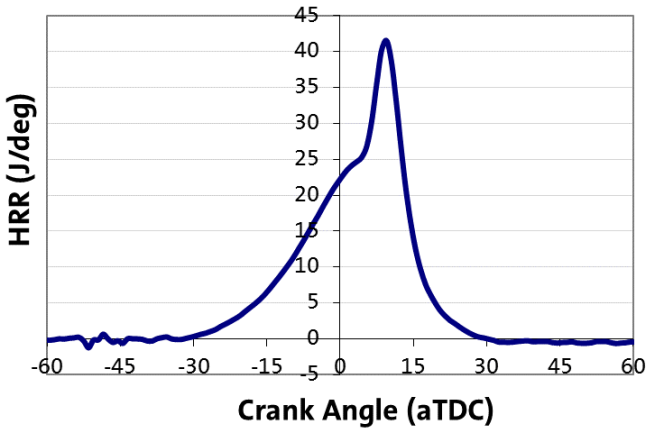
Quad injection strategy

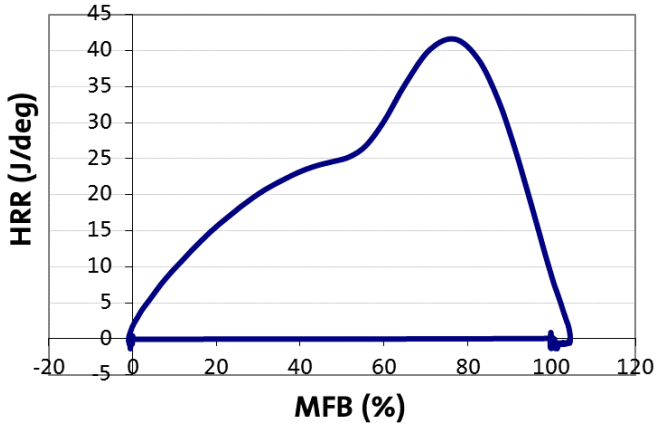
1. Significant stability improvement with slight increase in NOx emissions
2. More precise control of the amount of reforming & flame



# Technical Accomplishments and Progress

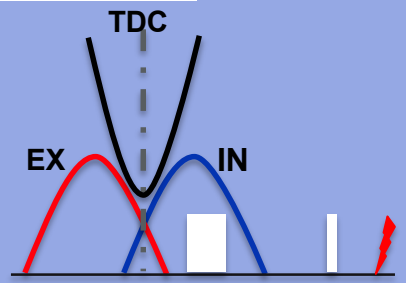
- WOT MAP = 95 kPa; w/ EGR
- High lift camshaft (Positive Valve Overlap) for internal residuals
- High efficiency, low noise and robust → NOx emissions

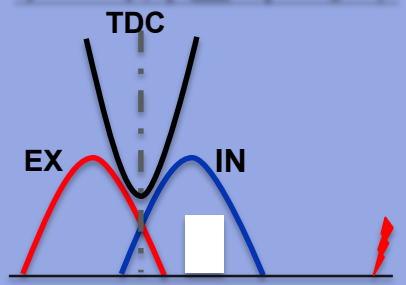



Torque (Nm)

Combustion Strategy III (plasma assisted auto-ignition) → Lean LTC during PVO operation (**NOx emissions**)




Speed (rpm)

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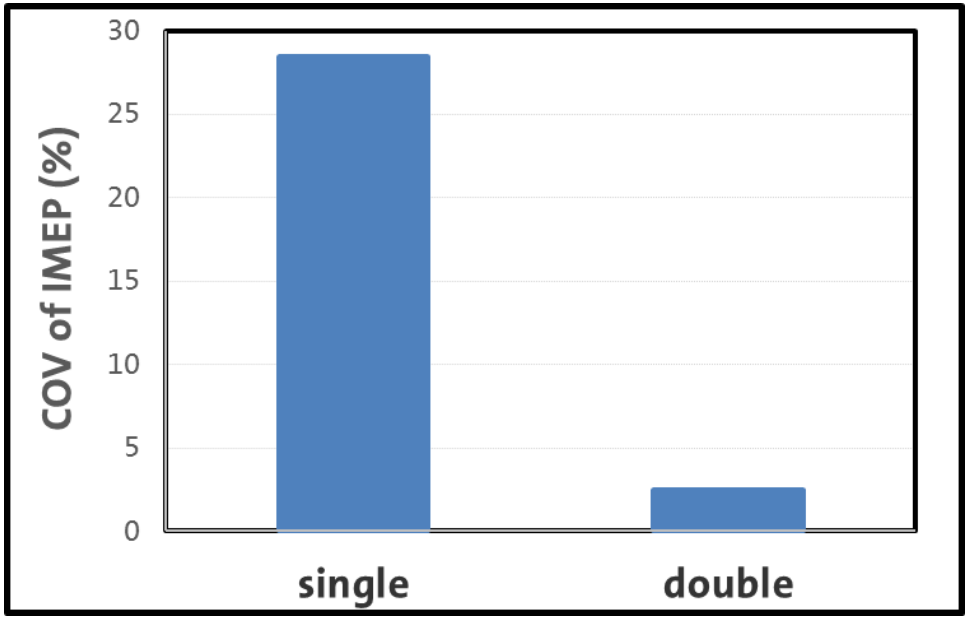
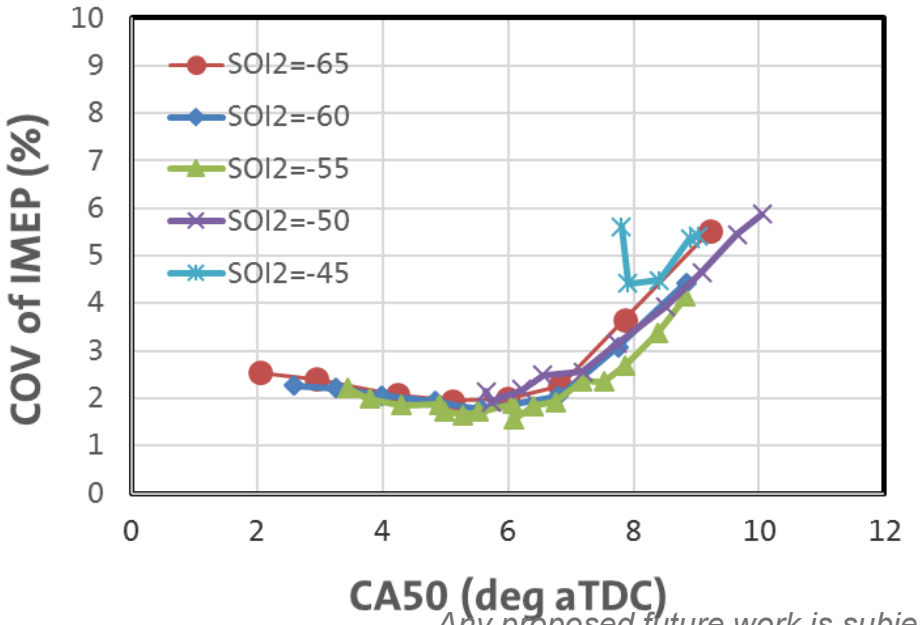
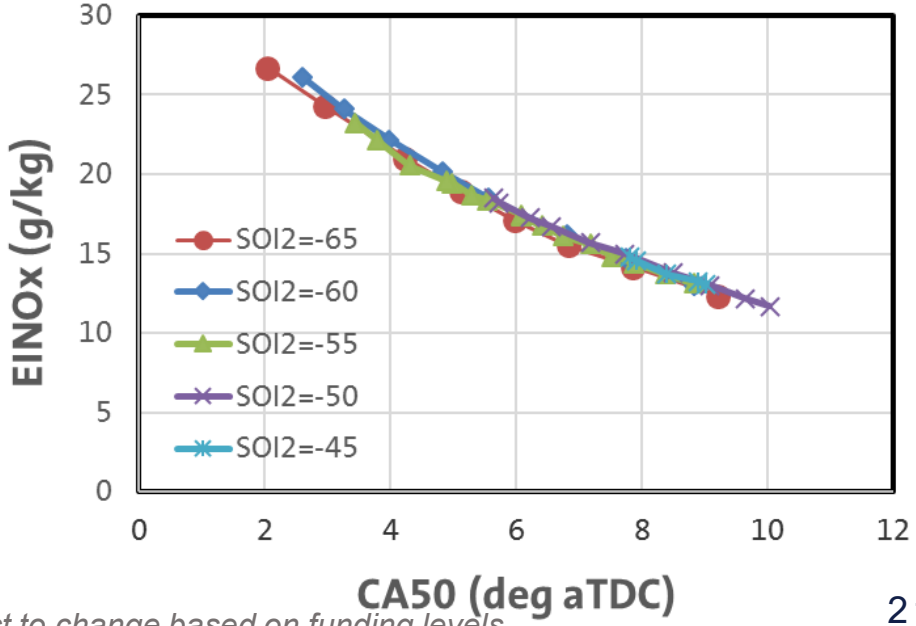



## Improve NOx-COV Trade-off

- 2000 rpm, 4.5 bar BMEP
- PVO operation
- 10% EGR
- Combustion phasing is a key parameter to obtain the best trade-off between NOx emissions and combustion stability

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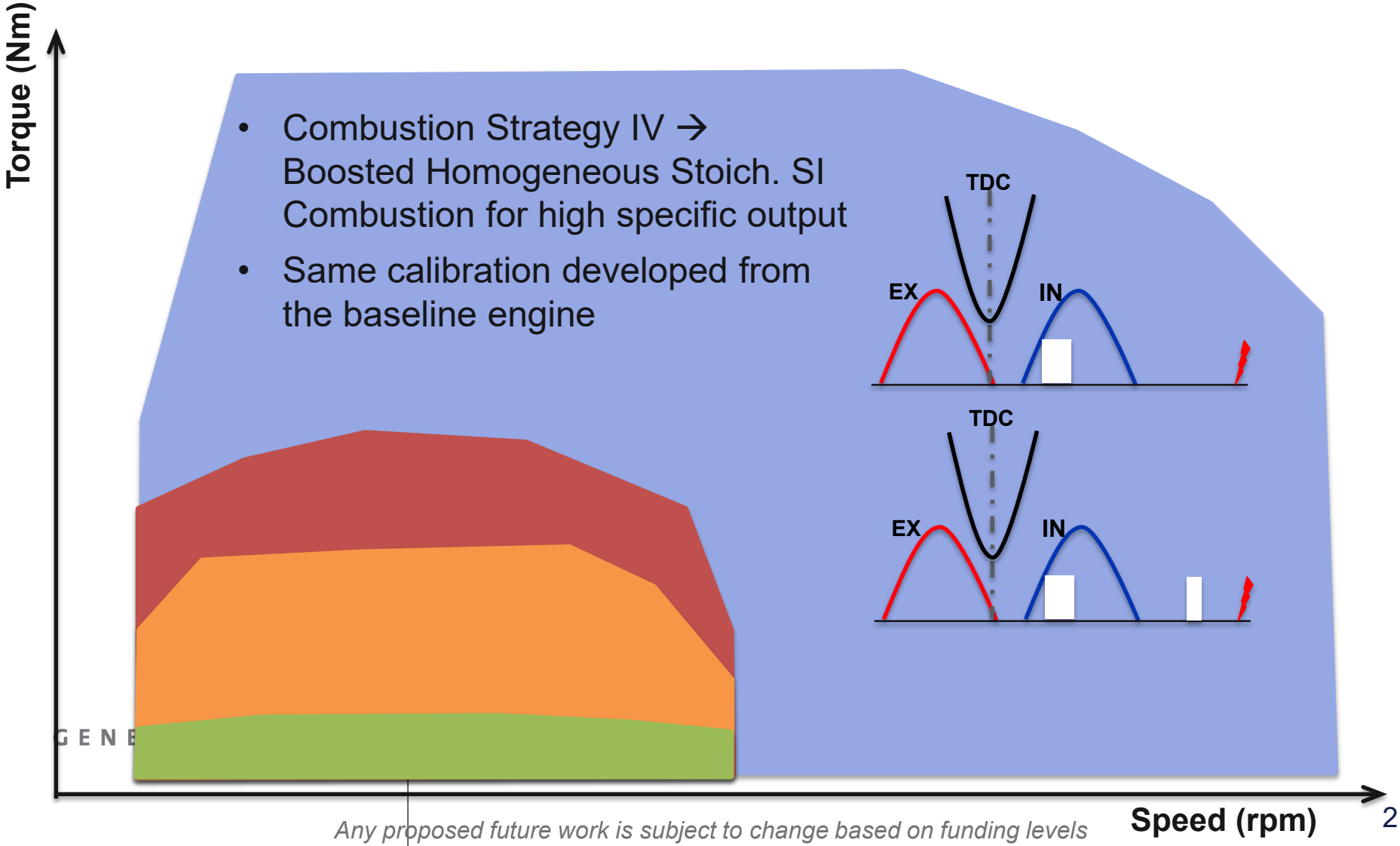


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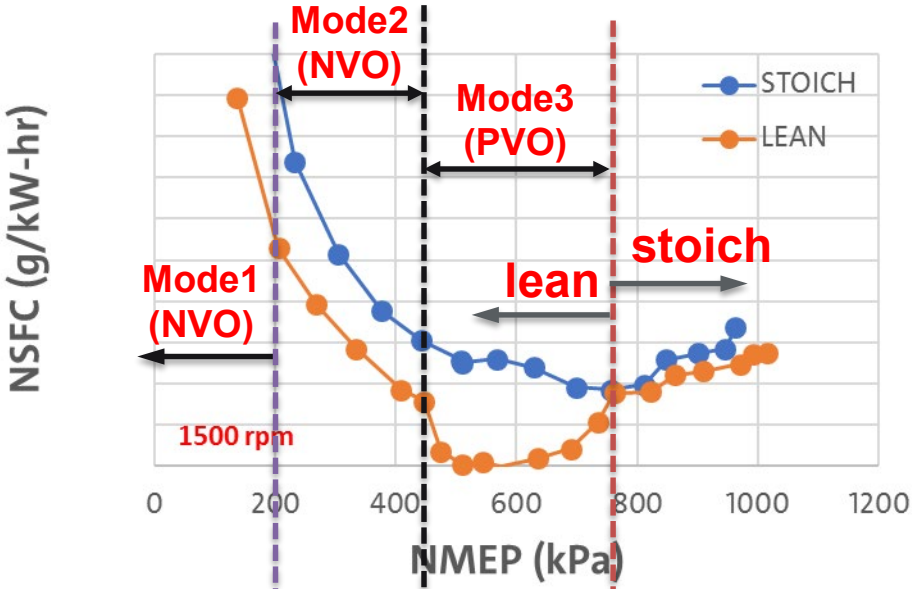


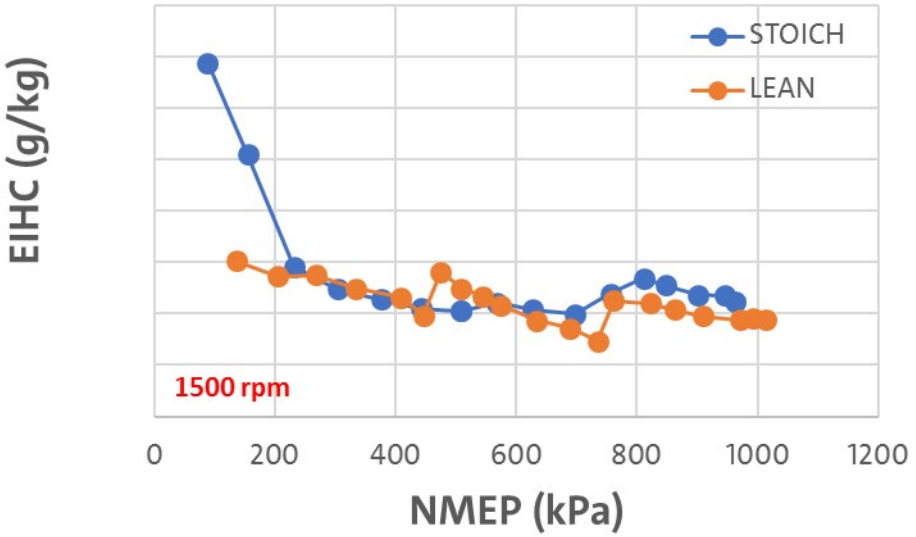


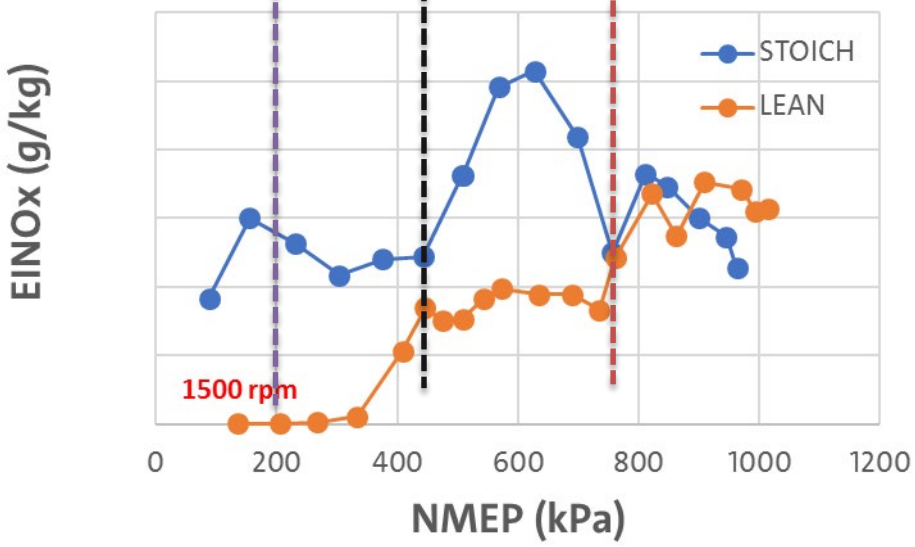


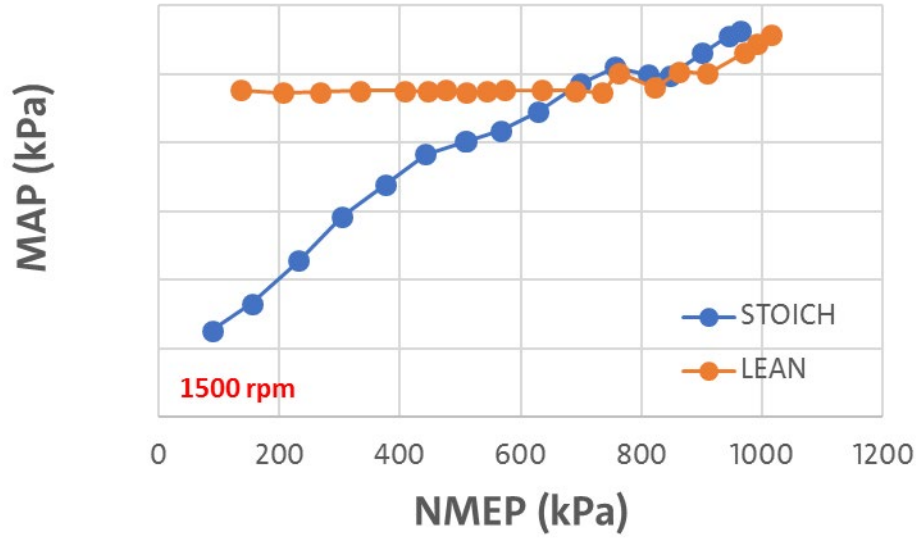


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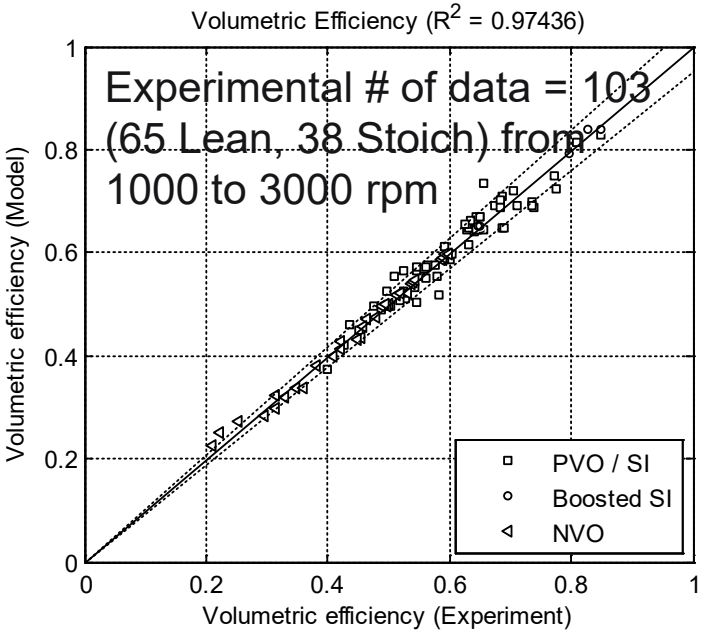
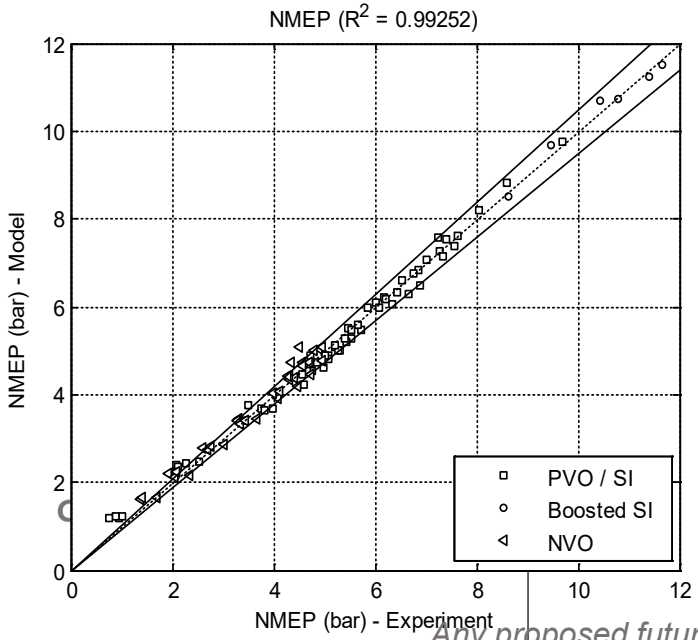
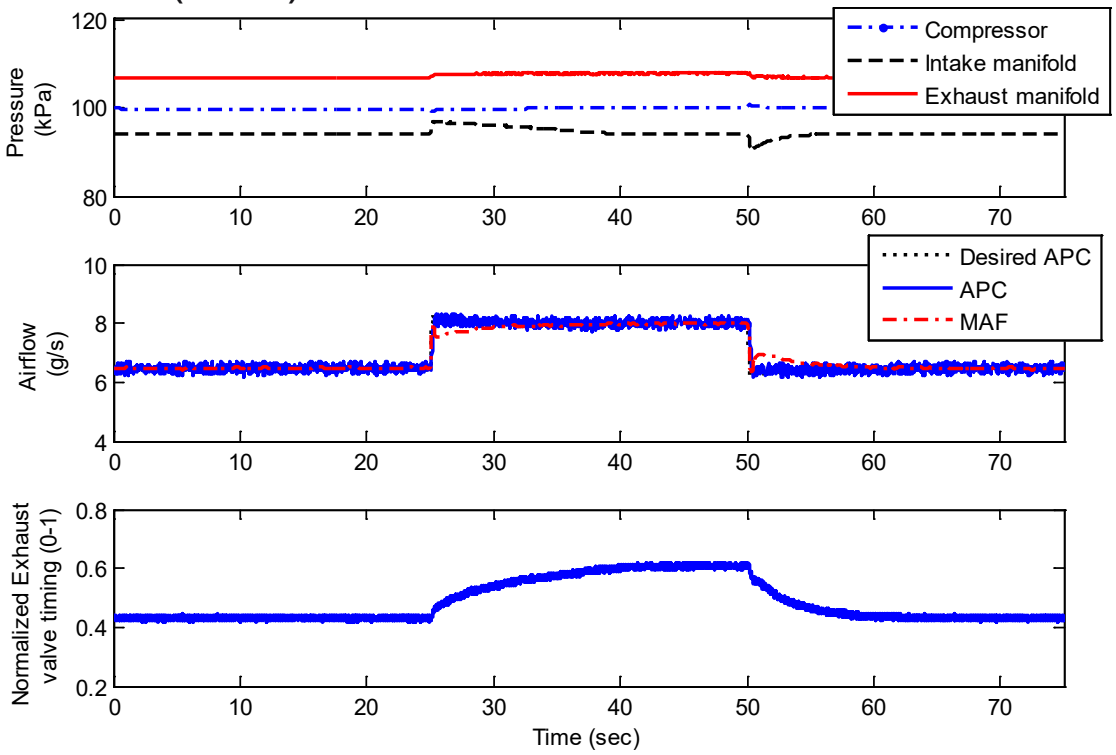
# Technical Accomplishments and Progress




An air charge control strategy for NVO and PVO mode is developed based on APC model and the partial air pressure in the intake manifold, which is estimated using a feedback from measured mass airflow (MAF).




Simulation result with the air charge control strategy is applied when the LTC engine is operated in NVO mode.



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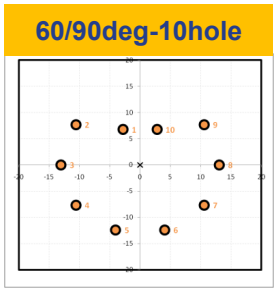
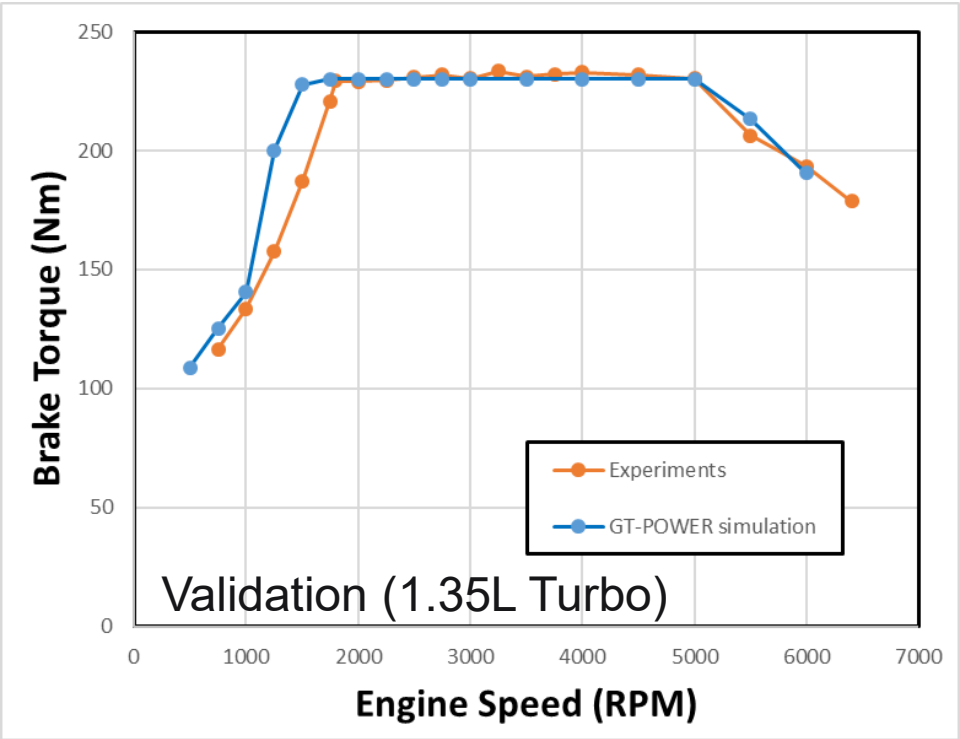
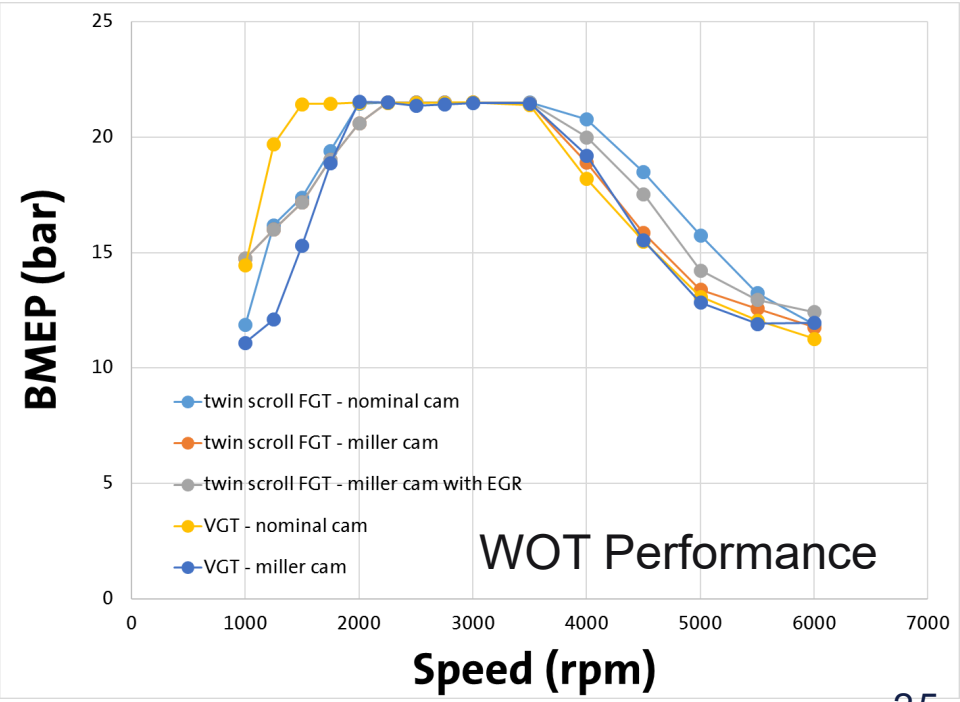
# Collaboration and Coordination

- **FEV** – GT-POWER modeling support for WOT studies to reduce baseline calibration efforts and hardware risk
- **DELPHI** – Fuel injector supplier due to the better performance of closely-spaced multiple injection.
- **Federal Mogul** – Worked together for the development of GBDI
- **BASF** – Worked together for the development of aftertreatment system



# Proposed Future Work and Challenges

- Refine low temperature combustion, control, and aftertreatment for smooth transient operation
- Develop a noise control strategy when EGR mismatches during transient operation
- Develop mode-switching strategy to prevent misfire or partial burn during mode change
- Demonstrate robust operation over hot FTP – fuel economy benefits and emissions results consistent with objectives
- Demonstrate robust operation over cold FTP – fuel economy benefits and emissions results consistent with objectives



*Any proposed future work is subject to change based on funding levels*

# Summary

## Low Temperature Combustion Engine

- Complete the development of homogeneous stoichiometric SI calibration and controls
- Successfully demonstrate FTP cycle test (both UDDS and HWFET) for homogeneous stoichiometric SI operation
- Develop the methodology of combustion phasing control for various modes of low temperature combustion
- Extend the lean low temperature combustion regime using multiple injection, EGR and valving strategy
- Complete extensive evaluation of GBDI system
- Complete the development of LTC calibrations and control

# Thank You !!!